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WAVE-POWERED UNMANNED SURFACE VEHICLE AS A STATION-KEEPING GATEWAY NODE FOR UNDERSEA DISTRIBUTED NETWORKS

by

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September 2012

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By analyzing data from a long-duration deployment of four wave-powered unmanned surface vehicles called Wave Gliders, an assessment of operating characteristics informs the potential utility of the Wave Glider in an undersea distributed network as a replacement for a moored communications gateway buoy. Specifically, the wave-powered propulsion system is analyzed to assess endurance, operability, and application in an underwater distributed network as the gateway node. The results of the study serve to identify the parameters for an experiment designed to test the Wave Glider as a station-keeping gateway node.

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ABSTRACT

By analyzing data from a long-duration deployment of four wave-powered unmanned surface vehicles called Wave Gliders, an assessment of operating characteristics informs the potential utility of the Wave Glider in an undersea distributed network as a replacement for a moored communications gateway buoy. Specifically, the wave-powered propulsion system is analyzed to assess endurance, operability, and application in an underwater distributed network as the gateway node. The results of the study serve to identify the parameters for an experiment designed to test the Wave Glider as a station-keeping gateway node.

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List of Acronyms and Abbreviations

ADCP	Acoustic Current Doppler Profiler
ASW	Anti-Submarine Warfare
COTS	Commercial Off The Shelf
CSD	Communications at Speed and Depth
GPS	Global Positioning System
ISR	Intelligence, Surveillance, Reconnaissance
LRI	Liquid Robotics, Inc.
MBARI	Monterey Bay Aquarium Research Institute
METOC	Meteorology and Oceanography
NDBC	National Data Buoy Center
NOAA	Naval Oceanographic and Atmospheric Administration
RIMPAC	Rim of the Pacific exercise
SATCOM	Satellite Communications
SBIR	Small Business Innovation Research
SHARC	Sensor Hosting Autonomous Remote Craft
SPAWAR	Space and Warfare
UDN	Underwater Distributed Network
USN	United States Navy
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
WAHAS	Wave Actuated Horizontal Array Stretcher
WGMS	Wave Glider Management System

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CHAPTER 1: Introduction

1.1 Background

The undersea distributed network (UDN) is a growing category of unmanned systems operating in a domain that cannot otherwise be influenced due to logistics and cost. Undersea distributed networks utilize acoustic signals and sound propagation to pass information under the surface of the water. From intelligence, surveillance, and reconnaissance (ISR) missions, to unmanned underwater vehicle (UUV) control, to communication at speed and depth (CSD) with submarines, underwater networks have potential to become force multipliers in undersea warfare (USW).

In order for the data transfer that occurs under the surface of the water to be useful, the communications must be converted from an acoustic signal to an electromagnetic signal at the air/water interface. Today, that conversion is conducted via gateway nodes equipped with both acoustic modems and satellite communication (SATCOM) modems. These modems are part of moored buoys that are anchored in strategic locations within the network where they can best receive the acoustic signals from the undersea network.

The gateway buoys used currently have several drawbacks that make them a weak link in the network. Moored buoys can be expensive, especially in deep water, and they require a significant amount of maintenance to ensure they remain in the proper location and operate as designed. Buoys are also vulnerable to tampering and collision by maritime vessels. Deep ocean buoys have significant watch circles, on the order of miles, depending on the depth of the water they are moored in, as the mooring scope is greater than the water depth.

A potential alternative to the moored gateway buoy is an unmanned surface vehicle (USV). In 2005, the US Navy advertised a small-business innovative research (SBIR) topic calling for the development of a station-keeping gateway node, called a 'gatekeeper' [5].

This thesis discusses the potential for one such USV, the Liquid Robotics' (LRI) Wave Glider, as an unmoored, station-keeping gateway node.

1.2 Objectives

The objective of this thesis is to determine if the Wave Glider could be an effective replacement to the moored gateway node. To investigate the practicality of the Wave Glider as a gateway node, the open-ocean performance of these USVs in the 2011-2012 PAC X experiment is examined. In order for the Wave Glider to be used as a gateway node, it must be able to loiter for weeks and months at a time, as well as maintain station or reposition in poor weather or sea conditions where the UDN is deployed.

This thesis attempts to make that determination.

1.3 Scope

For this research, the study is limited to the Wave Glider USV and its potential use in undersea distributed networks, using data supplied from the PAC X experiment and previous work on Wave Glider performance.

1.4 Relevance

This research does not yield a definitive answer as to the feasibility of the Wave Glider to serve as a gateway node. The PAC X experiment was designed as an oceanographic data-gathering mission and as such lacks the robustness needed to conduct a full-scale analysis of Wave Glider performance. Nevertheless, PAC X does provide significant insights into what is needed to conduct such an analysis and is of considerable value for future experiments using the two Wave Gliders possessed by the Naval Postgraduate School.

1.5 Organization of Thesis

In Chapter 2 this thesis discusses the history of the Wave Glider and its applications, UDN concepts, and the PAC X experiment commissioned by LRI as a demonstration exercise for the Wave Gliders. Chapter 3 gives an overview of the history of wave-powered propulsion and wave-energy harvesting, as well as the theory behind the operation of a wave-powered vehicle. Chapters 4 and 5 analyze the performance of the Wave Gliders during their transit from Central California to Hawaii and a detailed look at a few specific events along the way. Chapter 6 discusses future work, along with suggestions for follow on experimentation. Chapter 7 gives recommendations for Wave Glider use in Seaweb and other DOD applications.

CHAPTER 2:
Background

2.1 History of Wave Glider and Applications

The Wave Glider USV was initially developed in 2005 as a substitute for a buoy in a system designed to listen underwater sound. The story goes that a wealthy executive commissioned a project to help him listen to humpback whale songs in the bay beside his home on the big island of Hawaii. During the design process and subsequent prototyping, LRI was formed in 2007 to further the research and development of the Wave Glider concept [6].

The Wave Glider is an ocean wave-propelled USV with a two-body design. The lower 'glider' portion of the vehicle is tethered approximately seven meters below the upper 'float' portion of the vehicle via an umbilical as shown in Figures 2.1 and 2.2. The float and glider work in tandem to propel the vehicle through the water using the energy harvested from the wave action in the ocean. As the float rises and falls with the wave action on the surface, the glider portion, in relatively stationary water 7 meters below the surface, converts the vertical movements produced from the coupling between the vehicles into forward thrust. Since the glider portion of the vehicle is below most of the surface wave action in the majority of sea states, the "wings" attached to the glider rotate up and down with the wave action, causing forward thrust, much like the tail fin on a dolphin. As the glider portion is propelled forward by the wings, the float portion is pulled along via the umbilical attachment. Some Wave Gliders have been outfitted with shorter umbilicals to allow for shallow water operations; however, empirical studies have shown greatest efficiency with the seven-meter length [6].

The Wave Glider's propulsion system is purely mechanical, with no electric power used or produced in the process. There are two solar panels attached to the float portion of the Wave Glider that gather energy to supply electricity for the navigation and communication systems, as well as for the payload sensors installed onboard. Onboard batteries store some of the energy harvested by the solar panels for use when power demand exceeds the solar panel supply, or when weather conditions and time of day limit solar-panel output. The vehicle can operate for significant amounts of time without solar energy using battery power and cycling the hotel load to maximize endurance. The longest recorded operation with no ability to recharge the batteries was 23 days [7]. The solar panel performance and their electrical output depends on many

Figure 2.1: Wave Glider major components and physical layout provided by LRI

factors, including latitude, time of year, cloud cover, fog, and angle of the sun's rays.

Wave Gliders are controlled and navigated using an Iridium satellite link, GPS, and rudder remote control. Given these external communications, the vehicle can be classified as semi-autonomous. The vehicle is sent waypoint instructions using the Wave Glider Management System (WGMS), a LRI proprietary control software that provides control via internet. Some vehicles, especially those in service for military applications, are controlled through the same Iridium link, but are connected via other management systems that better match the users needs and existing infrastructure [8].

Many applications have been devised for the Wave Glider ranging from buoy replacement to oil-spill monitoring. It is appropriate to describe the Wave Glider's applications by using the Department of Defense's designation for the vehicle, "Sensor Hosting Autonomous Remote Craft" (SHARC). The Wave Glider is predominantly a platform for deploying a set of sensors in a maritime environment. The design can support various instruments, as long as they meet the size, power and environmental constraints and can be integrated into the existing software architecture. Since 2007 multiple Wave Gliders have been deployed with instruments such as dissolved oxygen sensors and weather stations for oceanographic work, hydrophones

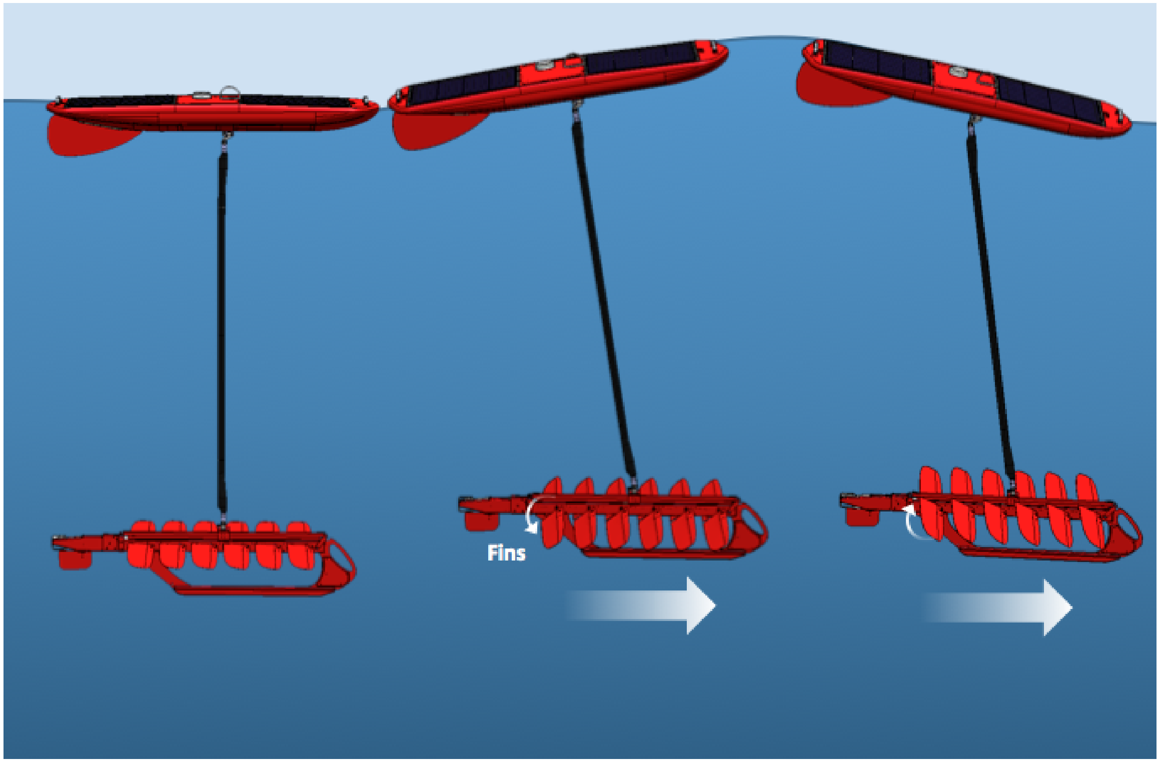


Figure 2.2: Wave Glider motion in wave action from [1]

for acoustic monitoring of marine mammals, and petroleum detection devices for oil and gas developers [9]. Figure 2.3 shows the payload bays and design of the float body.

For the Department of Defense, the Wave Glider is an interesting platform for work within several communities. From the obvious players like Naval Oceanography and intelligence organizations, the persistence at sea afforded by the Wave Glider allows is beneficial. Wave Gliders have already been deployed by the Navy as weather stations during fleet exercises and as ISR platforms. The vehicle's low profile while floating on the surface of the water presents little visible cross section.

2.2 PAC X Experiment and Data Gathering

In November of 2011 LRI deployed four Wave Gliders on a transpacific voyage as a demonstration of their vehicles. LRI challenged the research and industrial community to find interesting ways to use the data collected during the crossing. The exercise, known as PAC X, is expected to be the longest distance ever traveled by a USV. The four Wave Gliders all left from Central California and transited to Hawaii. From there, two vehicles headed to Australia and the other

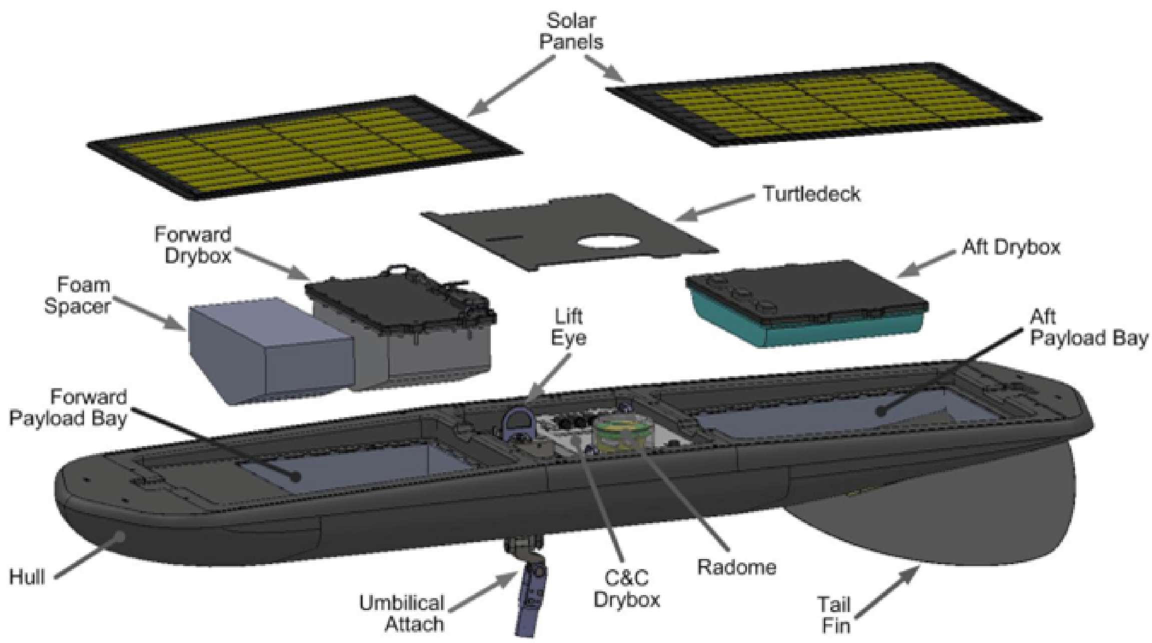


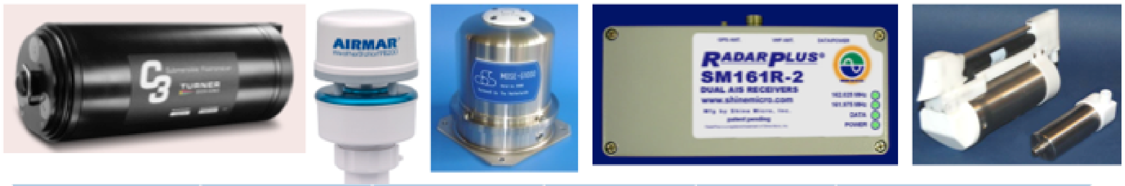
Figure 2.3: Wave Glider float body exploded view and payload housing provided by LRI

two to Japan. Each of the four vehicles identified for the transit were christened with names associated with famous ocean explorers. The two gliders heading to Australia are named *Papa Mau*, in honor of famous Micronesian navigator Pius Piailug, and *Benjamin*, in honor of American scientist and Gulf Stream pioneer Benjamin Franklin. The two gliders traveling to Japan are named *Piccard Maru*, in honor of famous Swiss oceanographer and deep ocean explorer Jacques Piccard, and *Fontaine Maru*, in honor of the father of modern oceanography Matthew Fontaine [10].

Each of the four vehicles are identically equipped with the same sensor payload. These include a weather station for wind speed, barometric pressure sensor, air temperature sensor, fluorometer for dissolved solid measurement, and various other sensors as listed in Table 2.1. The payload deployed on the four Wave Gliders is designed to measure ocean parameters that are currently measured by oceanographic research vessels and moored buoys deployed across the Pacific. Each of the vehicles has the same payload in order to determine performance differences and changes in ocean conditions between the Wave Gliders as they transit [10].

The four Wave Gliders follow a course that is issued to the vehicles via the WGMS and the Iridium satellite link. GPS fixes are used to track vehicle position and maintain heading. The

Table 2.1: Liquid Robotics instrument payloads on PAC X Wave Gliders from [1]



Instrument	Measurement	Units	Sensor Location	Sample Rate	Telemetry Rate
GPS	Position	Decimal Lat, Lon	Float top deck	15s	5 min, last sample only
Engineering Data	System Status	Various	Internal	Various	5 min
Power Data	Solar/Battery Status	Various	Internal	Various	60 min
Backup GPS	Position	Decimal Lat, Lon	Mast deck	Single acquisition	12 hour
Weather Station	Air Temp	Degrees C	1m mast	1 Hz	10 min average every 10 min
	Barometric Press	mbar	1m mast	1 Hz	10 min average every 10 min
	Wind Speed & Dir	Knots, Degrees true	1m mast	1 Hz	10 min average every 10 min
	GPS	Decimal Lat, Lon	1m mast	Last position	10 min
AIS Receiver	Nearby ships	AIS Report	0.5m whip antenna	Special. Every 20 min, and upon new acquisition.	
Water speed	Float water velocity	Knots	Float belly (-0.1m)	Continuous	1 min average every 5 min
G10 Camera	Down-looking images	jpg Images	Float belly (-0.1m)	On Demand	On Demand
Turner C3 Fluorometer	Chlorophyll A	Raw fluoroescence units	Float belly (-0.1m)	2 min	Group of 7 samples every 14 min
	Crude Oil	Raw fluoroescence units	Float belly (-0.1m)	2 min	14 min
	Turbidity	Raw fluoroescence units	Float belly (-0.1m)	2 min	14 min
	Water Temp	Degrees C	Float belly (-0.1m)	2 min	14 min
Datawell MOSE-G Wave Sensor	Significant Wave Height	Meters	Mast deck	2Hz	512 point average every 30 min
	Average Period	Seconds	Mast deck	2Hz	512 point average every 30 min
	Peak Period	Seconds	Mast deck	2Hz	512 point average every 30 min
	Peak Direction	Degrees C	Mast deck	2Hz	512 point average every 30 min
Seabird GPCTD+DO	Pressure		Float belly (-0.1m)	10 sec	8 sample average every 10 min
	Temperature		Float belly (-0.1m)	10 sec	8 sample average every 10 min
	Conductivity		Float belly (-0.1m)	10 sec	8 sample average every 10 min
	Dissolved Oxygen		Float belly (-0.1m)	10 sec	8 sample average every 10 min

data gathered during the experiment are uploaded to a public website and can be accessed by anyone who registers with the company as a subscriber [10].

For the purpose of this research, several of the data sets are analyzed to assess the performance of the Wave Gliders during their crossing. Since the vehicles operate using wave propulsion technology, data on ocean conditions are used to determine performance. Those parameters include wave height and period, wind speed, vehicle water speed, and GPS record. The Wave Glider has a Datawell MOSE-G wave sensor mounted on the float portion of the vehicle that acquires all of the data on wave conditions. The wave height is measured in meters, and the period is measured in seconds between wave peaks. The wave sensor data are reported every 30 minutes, averaged at 512 points during that 30 minutes. Water speed is measured on the float portion of the vehicle as well, and is reported in nautical miles per hour (knots). Speed over water is reported as a one minute average every five minutes. Windspeed data in knots are taken from the Airmar weather station every ten minutes, averaged over the last ten minutes. Lastly, GPS data are sampled every 15 seconds and reported every five minutes [10].The website for the PAC X is http://pacxdata.liquidr.com.

During the transit from San Francisco Bay to Hawaii, the Wave Gliders experienced Eastern Pacific Ocean conditions. At various points along the way, the vehicles stopped and station kept in the vicinity of moored ocean buoys that are deployed by the National Oceanographic and Atmospheric Administration (NOAA) to monitor ocean conditions throughout the Pacific. The two vehicles heading to Australia will cross the Equator and observe the environmental conditions along the way, while the other two will detour across the Marianas Trench on their way to Japan. Observing how the vehicles respond to the changing ocean environment and conditions in areas like the equatorial region will provide insight into the overall operational characteristics of the Wave Glider platform. As of this writing, the four Wave Gliders have crossed the international dateline on their way to Japan and Australia.

As part of the PAC X experiment, LRI is making available all of the data collected from the vehicles during their transit in near real time. The amount of data is staggering. All of the data is published on the LRI website and can be downloaded in various formats for ease of compilation and use [10]. For this research, the data sets are downloaded in CSV format and uploaded into Matlab for analysis. The data sets can be filtered using several parameters.

The Wave Glider performance characteristics are the focus of this research, so only a subset of the available data parameters are examined. To effectively analyze the performance, relevant data included those from the Airmar PB200 weather station, the Datawell MOSE-G directional wave sensor, and the onboard GPS receiver. For this research, the data are from the transit of Wave Glider *Benjamin* from Monterey Bay, where sea trials were conducted at the beginning of the experiment, to the Big Island of Hawaii.

2.3 Undersea Distributed Networks and Need for a Gateway Node

UDN is a concept for future USW architectures integrating manned and unmanned systems. Seaweb, as shown in Figure 2.4, is such a system of underwater nodes that can communicate with each other over an extended range under the sea using acoustic communications. The system is designed with fixed nodes that are deployed on the sea floor and mobile nodes that can be repositioned based on mission requirements. Seaweb is designed for relatively shallow water environments and has been shown to be effective in delivering messages acoustically to

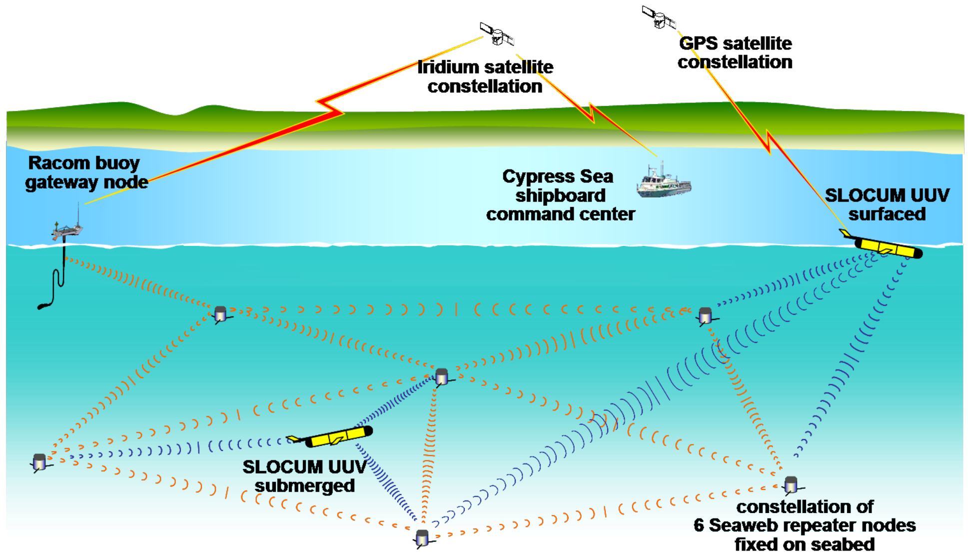


Figure 2.4: Seaweb artist rendering as depicted in [2]

submarines and gateway nodes that relay the communications via electromagnetic signals to shore for further use. Some missions demonstrated are oceanographic sensing, anti-submarine warfare (ASW) surveillance, sea-mine remote control, and CSD for submarines and UUVs [2].

Information gathered by sensors deployed in the Seaweb network is relayed between nodes and to a gateway node that acts as the interface between surface and subsurface. Here the information is forwarded via satellite signal or radio transmission in the electromagnetic spectrum. Currently, the gateway node in Seaweb is a buoy system that maintains location via a mooring to the ocean floor like that shown in Figure 2.5. Typical moorings can be as much as three times the depth of the water they are deployed in, or more. This large mooring scope causes ocean buoys to have larger watch circles as they are deployed in deeper waters. In order for the gateway node to effectively receive acoustic communications from the sensor and repeater nodes, it must maintain itself within communications range of the acoustic network. This can pose a challenge in the development of deep-ocean UDN systems [11, 12].

One of the challenges with implementing a deep-ocean UDN system is the gateway node link. At depths of 4000 meters, a moored buoy acting as a gateway node would have a watch circle on the order of 4000 to 6000 meters. Also, deep-ocean moorings are expensive and require significant maintenance. One alternative to a deep-moored ocean buoy gateway node is a USV, such as the Wave Glider [13].

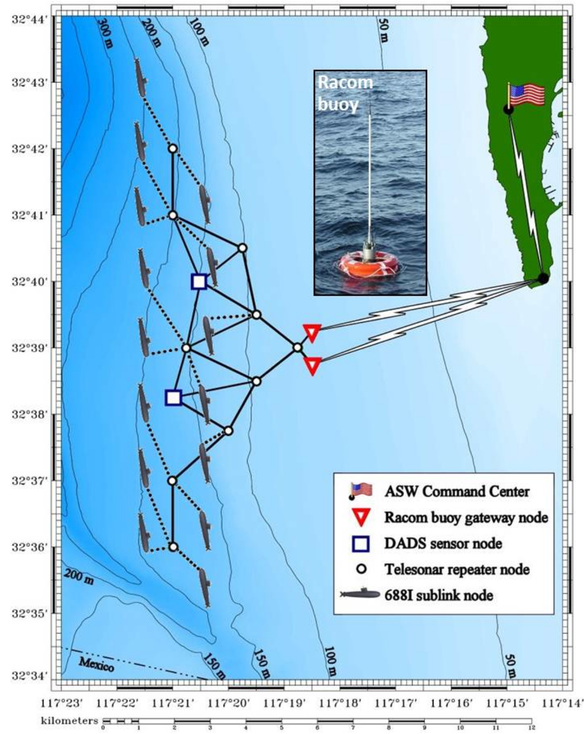


Figure 2.5: Current gateway buoy in Seaweb from [3]

On initial inspection, the Wave Glider appears to have some desireable characteristics that a deep-moored ocean buoy gateway node does not. The Wave Glider can be repositioned based on mission and stealth requirements, and may maintain smaller watch circles. There are some concerns with the robustness of the Wave Glider's propulsion system and its ability to keep station in the ocean conditions that may be encountered in some operational environments. An inspection of the Wave Glider's ability to operate in varying ocean conditions is needed to determine if the vehicle is suited for use as a replacement for a deep-moored ocean buoy.

Work has recently been completed on addressing some the the issues with placement of an acoustic modem on the vehicle, including drag and acoustic considerations. The conclusions determined that a tow body attached to the glider portion of the vehicle was an acceptable near-term implementation [13]. Tow bodies tested for other applications that are similar in size to that required for an acoustic modem are shown in Figures 2.6 and 2.7.

Figure 2.6: Pierside with a Wave Glider and tow body provided by LRI

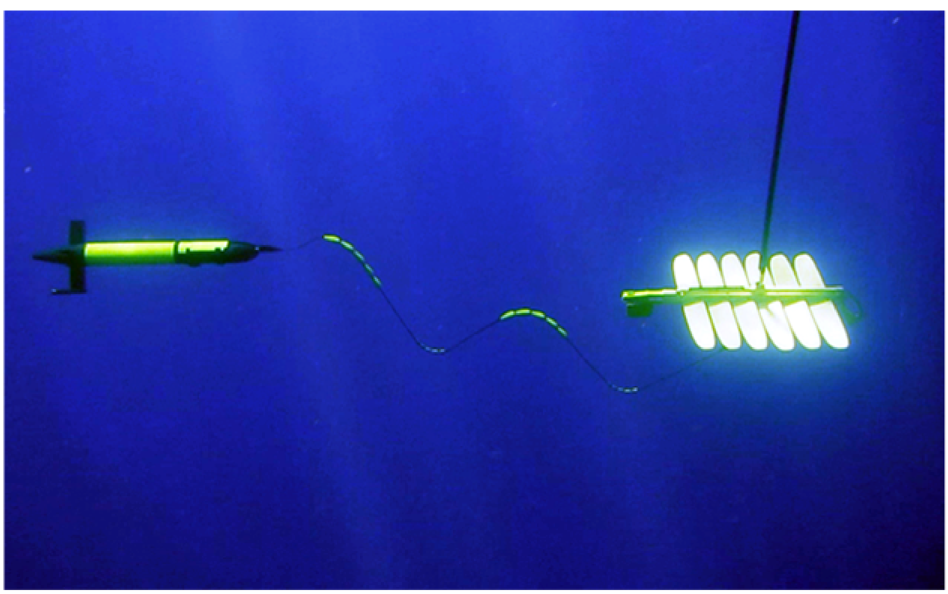


Figure 2.7: Wave Glider depoyed with a tow body provided by LRI

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CHAPTER 3:
Wave Glider Technology and Theory of Operation

3.1 Previous Work on Wave Energy Harvesting

The oscillatory motion of waves has been coveted for years as a renewable energy source for use as a power supply. Buoys that can produce power to operate onboard sensors and generators that run on air compressed by wave action near shores are just a few examples of the concepts that have been developed to use wave energy as a power supply [14,15]. The challenge has been finding a technology that is efficient enough to transfer enough of the energy harvested into a useful output [16].

Harvesting energy from the ocean is not a new concept and harvesting wave energy for horizontal propulsion has been explored at Naval laboratories since at least the 1970's. Theoretical and experimental work has determined the force generated by the oscillation of a wave set using a vehicle similar to the Wave Glider's lower body [17]. Engineers created an artificial environment and measured the tension via a force meter to characterize the forward thrust of the vehicle. By adjusting wave parameters and different materials for the vehicle, engineers were able to determine some characteristics of a wave-powered vehicle. The intended use of this wave-powered vehicle was to maintain a tension on a high-gain acoustic horizontal line array in the open ocean. The vehicle, known as a Wave-Actuated Horizontal Array Strecher (WAHAS), was patented in 1976 [18]. Similarly, when LRI originally prototyped the Wave Glider, it was to enable acoustic monitoring of whale songs and telemetry to shore in real time without having to moor a buoy in the deep ocean [10].

3.2 Wave Power Theory and Operation

Kinetic energy in the form of sea-surface wave oscillations is transformed into horizontal thrust of the vehicle using the flipper action of the lower body of the Wave Glider. As the buoyant float body of the vehicle is moved up and down with the wave oscillation, the lower glider body's wings produce a forward thrust on both the upward and downward motion of the wave action. Theory predicts that as wave amplitude increases and wave period decreases, more wave power will be available to be transferred into forward thrust. Based on LRI testing on early prototypes, this relationship appears to hold [4].

During testing of the WAHAS in 1982, a theoretical predictive equation was developed for the force produced by a wave-powered vehicle very similar to the Wave Glider design [17]. The resultant force F_{max} is:

$$F_{max} = C_D \frac{\rho V_{max}^2}{2} S_0 \tag{3.1}$$

where C_D is the drag coefficient of the thrust flippers, ρ is the density of seawater, V_{max} is the maximum vertical velocity of the vehicle, and S_0 is the surface area projection of the thrust flappers at a 45 degree angle. Maximum vertical velocity is:

$$V_{max} = \frac{2\pi R}{T} \tag{3.2}$$

where R is the amplitude of the wave and T is the period of the wave action [17].

Efficiency of the design is also important to the overall operation of the Wave Glider propulsion system, and theory has shown that the flipper action is efficient when compared with other modes of propulsion [19]. The problem with the flipper action in general is the finite amount of energy that can be harvested, limiting the net thrust.

Wave action in the open ocean is produced from the wind blowing over the water. As the wind moves across the surface of the water, the turbulent action produces small waves with heights on the order of centimeters. As the wind continues to interact with these small waves, a pressure difference is created, making the wave larger and larger. The waves then coalesce with each other creating longer waves that travel significant distances and rise to significant heights [20].

Since the umbilical is not rigid and can twist, the float and glider are not always on the same orientation. The rudder is located on the glider portion of the vehicle, ensuring that the propulsive portion of the vehicle controls the heading of the Wave Glider. As the float body is pulled along by the glider body, the float interacts with surface waves and which alters its heading with respect to the glider. During the drift cycle of the Wave Glider thrust/drift propulsion action, the vehicle is even more succeptable to departing from parallel orientations.

Other testing has been conducted on the Wave Glider's performance [4] and seems to confirm that wave height is an important factor in determining the speed of the vehicle. Speed of the Wave Glider as a function of wave height and sea state is shown in Table 3.1. These tests, how-

Table 3.1: Wave Glider speed estimates as a function of sea state from [4]

Sea State	Significant Wave Height (m)	WG Speed (kts)	WG Speed (m/s)
Flat Calm	0	0	0
Sea State 0	0	0.25 - 0.5	0.13 - 0.26
Sea State 1	0 - 0.1	0.5 - 1.5	0.26 - 0.8
Sea State 2	0.1 - 0.5	1.25 to 2.0	0.64 - 1.03
Sea State 3+	0.5 - 1.25+	1.5 - 2.25	0.8 - 1.16
Long Mission Average	Variable	1.5	0.8

ever, were conducted in relatively calm seas with no significant weather events or currents. The tests were done in Monterey Bay, near ocean observation buoy M1 maintained by the Monterey Bay Aquarium Research Institute (MBARI). At 10 meters below the surface, measured currents were analyzed to determine if they have an effect on speed output of the propulsion system. The results showed no consistent effect on the speed of the Wave Glider in a low-current environment [4].

LRI has deployed vehicles across the Eastern Pacific and the Gulf of Mexico with similar results. In 2007, one Wave Glider experienced Hurricane Flossie and survived the incident. While the vehicle was unable to make significant headway during the storm, it survived with little damage to the vehicle [6]. Extremes in ocean conditions create the largest effects on operation of the Wave Glider. When there is no wave action at all or there is a major storm with swirling seas, the vehicle fails to make significant headway and cannot keep station.

Strong currents can have a significant effect on the performance of the Wave Glider. With a top speed of only around 1.5-2 knots, there are areas of the ocean where currents exceeding those values can work against the Wave Glider's ability to make way into the current. The Gulf Stream in the Atlantic Ocean and areas close to shore where tidal variations cause major current flows are examples of such conditions. Strong currents can inhibit the ability of the Wave Glider to keep station.

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CHAPTER 4: Long-Term Vehicle Performance Analysis

4.1 Performance Metrics

For the initial analysis of the Wave Gliders' performance during the PAC X experiment, a reconstruction of *Benjamin's* transit from Central California to Hawaii is performed. Several parameters are analyzed over the duration of the journey, from November 2011 to April 2012, to determine their effect on the propulsion system. Independant variables, including wind speed, wave height and wave period, as well as the dependant variable speed over water of the vehicle are examined in particular. The hopethesis of for this analysis is that Wave Glider speed depend on wave height and wave period.

The data gathered for the analysis includes speed over water at five-minute increments, average wind speed over ten-minute increments, and wave height and period at 30-minute increments. Currents are not directly measured by the Wave Gliders as they conduct their transit, but an attempt is made to determine what the currents were based on organic data available from the onboard sensors. All data analysis and graphs are completed using Matlab [21].

An approximation for the current vector at any give time can be calculated using speed over water, speed over ground, course over ground and vehicle heading [22]. Speed over ground and course over ground can be inferred from the GPS data, and speed over water is measured directly on the vehicle. Since the float body and the glider body are separated by a non-rigid umbilical, the two bodies can be and most likely are on different headings that diverge more as currents increase. Since the Wave Glider is a unique two-body system, the vehicle dynamics for operation in a current cannot be approximated the same way a traditional ship can be.

Based on the initial testing identified in previous work, [4, 17, 23] the most dominant environmental parameters that affect Wave Glider propulsion performance are wave height and wave period. Since wind is the dominant factor in the production of wave action, it is logical to include wind speed as a factor as well. These three parameters are the basis of the initial investigation into their effect on Wave Glider propulsion performance.

The Wave Glider propulsion system causes a cycling action where there is a thrust as the wings push the vehicle forward followed by a drift as the wings reposition and thrust again. Based on this action, if a speed measurement is taken during a thrust, the water speed recorded will naturally be higher than if the measurement is taken during the drifting period of the cyclic action. Since the thrust/drift cycle time is based on the dynamic wave period, a standard increment for measurement produces peaks and troughs in the measured water speed. There is also evidence that the downward and upward thrust actions have different thrust production [17]. This phenomenon also makes for a challenging current analysis, as the current will affect the vehicle differently during the drift than during the thrust.

After the launch of the four Wave Gliders a few miles out to sea off of San Francisco, they transited southward to Monterey Bay for initial testing and a calibration of all the onboard sensors. The vehicles finally set course for Hawaii in mid-December 2011. Wave Glider *Benjamin* is the focus of this analysis due to the higher fidelity of the data gathered compared with the other vehicles on the transit. One of the other vehicles, *Papa Mau*, suffered a loss of Iridium satellite link for a significant amount of time and another, *Piccard Maru*, was attacked by a shark later in the first leg of the trip, causing it to lose rudder control [10].

As a first look at correlation across experimental parameters, the factors are graphed as function of time, shown in Figure 4.1. It is useful to note that wave height and period, as well as wind speed, appear to be correlated. As wind speed increases, wave height and period increase simultaneously. Speed over water, the factor of importance as a metric of vehicle performance, does not appear to follow the same trends as the three environmental parameters over time, which is inconsistent with the hypothesis.

As the data are analyzed, one can see that there are outages in the data. Speed over water in several instances goes to zero for a significant amount of time, the longest of which was approximately a two-week period at the beginning of January where no water-speed data were reported. By examining the vehicle track based on GPS data in Figure 4.2, it is clear the Wave Glider did not stop moving during these periods, but continued to make way toward Hawaii. Because of these outages, an average of speed over water over the entire transit is not useful in estimation, as the zero speed skews the data. Based on GPS track distance and time of transit, the *Benjamin* averaged 0.91 knots for the trip to Hawaii. The peak wind speed observed was about 100 knots, and peak wave amplitude was over 15 meters during the transit from San Francisco to Hawaii. Average wind speed was between 15 and 25 knots, average wave amplitude was around two meters, and average wave period was around ten seconds.

The Wave Glider uses an algorithm that constantly corrects rudder angle to maintain the vehicle

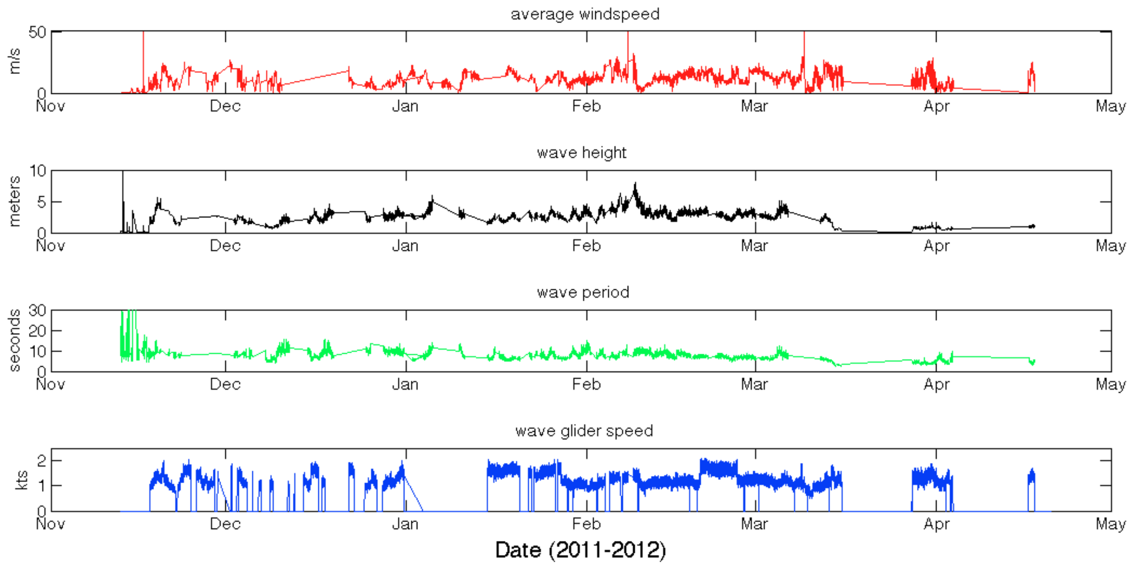

Figure 4.1: Wind speed, wave height and period and water speed from Wave Glider *Benjamin* transit from San Francisco, CA to Hawaii

on the prescribed track. During the transit, *Benjamin* was able to maintain its course consistently based on the GPS track. If there were strong currents or a large storm with swirling seas that could affect the operation of the propulsion system enough to prevent the vehicle's ability to maintain track, there is little evidence in the data provided. One notable exception is discussed in the next section.

4.2 Performance Predictions Over Long Term Deployments

The Wave Glider, with its wave-powered propulsion system, has shown during the PAC X experiment that it can consistently follow a prescribed track and reach a waypoint. Three vehicles finally reached Hawaii in the middle of March 2012 and the fourth, *Piccard Maru*, which was attacked by a shark and lost rudder control, made it within a few hundred miles before being retrieved by a passing vessel and delivered to LRI in Hawaii.

Over longer-term deployments, the average speed of the vehicle becomes more indicative. This is a result of the consistent ocean conditions over longer periods and the averaging of exceptional events as the time record increases. This is not unexpected and has been observed on other long-term deployments of the Wave Glider USVs [7].

How this performance relates to the ability of the Wave Glider to operate as a gateway node

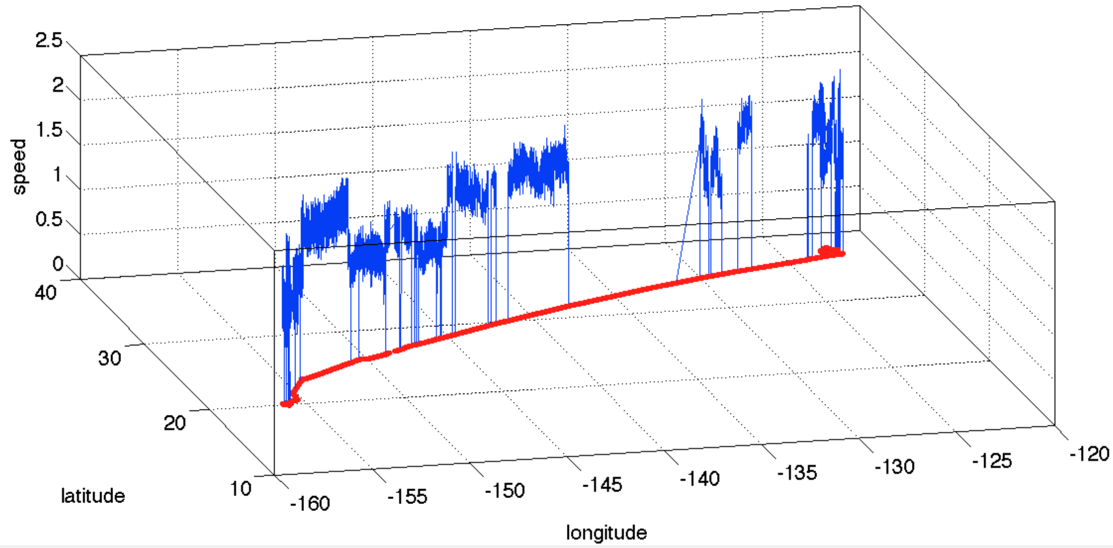

Figure 4.2: GPS track from Wave Glider *Benjamin* transit from San Francisco, CA to Hawaii

for a blue-water undersea distributed network is less clear. While the need for a long-term deployable platform is necessary, the vehicle will actually be station keeping and not transiting significant distances. *Benjamin* conducted a station-keeping operation around an oceanographic buoy north of Hawaii for data correlation analysis that is examined in the next chapter.

4.3 Impact of Outages

Papa Mau experienced an Iridium satellite network outage for an extended period of the voyage and all the vehicles were subject to power cycling to onboard sensors for power conservation efforts. A communications gateway node requires constant connectivity with the undersea network. The acoustic modem and satellite communication equipment would need to be powered from the onboard solar panel and battery system within the vehicle and the outages noted in the water speed sensor during PAC X are a concern for the continuous operation of the acoustic modem and SATCOM equipment needed for the gateway function.

CHAPTER 5: Detailed Analysis

5.1 Detailed Look from 26 February 2012

As the analysis of the Wave Glider deployments proceeds, it is necessary to focus on small portions of the transit to conduct more thorough studies of the performance of the vehicle. Aboard *Benjamin*, from 21 February until 06 March 2012, interesting discrepancies in the data are observed. Specifically, on 26 February 2012, *Benjamin* had an abrupt decrease in speed over water from an average of 1.7 kts to an average of 1.2 kts. This 30% reduction was not immediately attributed to the independant data. It is interesting to note that at this specific point on the journey, a 20-degree course change was made from an approximate heading of 235 degrees to a heading of close to 255 degrees.

During this turn, Wave Glider *Benjamin* circled one of NOAA's National Data Buoy Center (NDBC) weather observing buoys. The buoy is identified as Station 51000. Station 51000 is deployed in a water depth of 4096.5 meters and has a watch-circle radius of 4275 meters [24]. The buoy is centered on a latitude of 23.54 North and longitude of 154.15 West. *Benjamin* made a circumnavigation of this buoy's location using a hexagonal course, displayed in Figure 5.3. After circling Station 51000 four times, *Benjamin* continued westward at an approximate heading of 255 degrees.

Since this circumnavigation of a sensor station is indicative of the type of operation that would be expected in an operational open-ocean UDN system, it is of particular interest to this research. *Benjamin* circled the station 51000 buoy four times over the course of 48 hours and then continued on towards Hawaii. The vehicle maintained the same speed throughout the station-keeping exercise and based on the GPS track recorded, was able to maintain course. During the five passes around the expected location of Station 51000, the vehicle deviated by less than 100 meters, as shown in Figure 5.2.

Based on this performance, *Benjamin* could easily close the watch circle of the buoy and circle at much smaller diameters, if desired. The dimensions of the hexagonal track are 4000 meters by 2000 meters and these results indicate watch-circle radius inside of 500 meters is practical.

To determine the cause of the abrupt change in water speed that occurred on 26 February 2012,

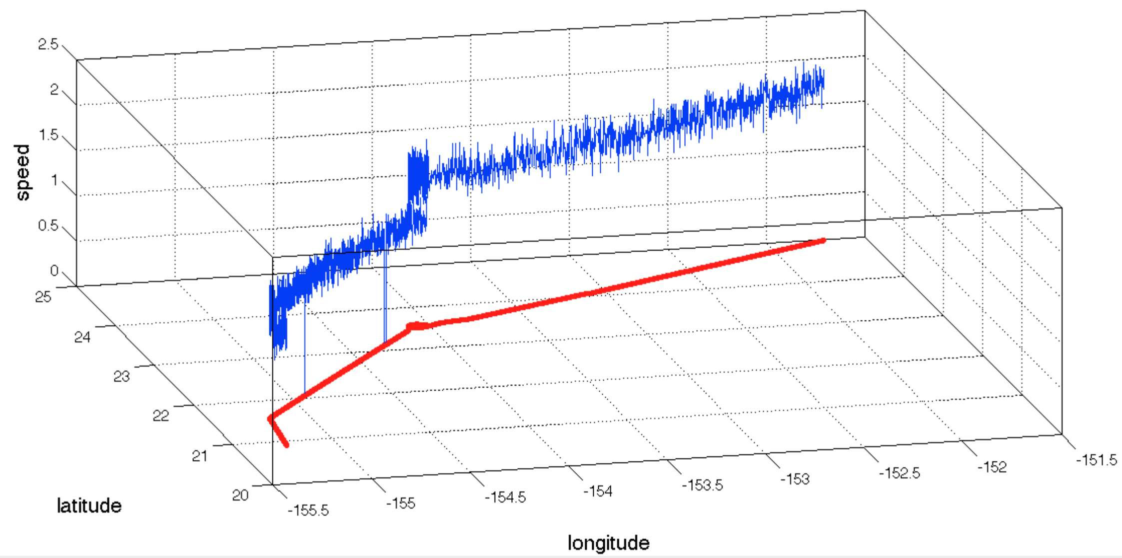

Figure 5.1: Wave Glider *Benjamin* transit 26 February 2012 to 06 March 2012

which is believed to result from a change in the current vector, the speed over water during the circle maneuver is investigated in further detail. If there was a current acting on *Benjamin* during transit that caused a reduction in speed during a course change, the water-speed reduction would be evident on parallel legs in the hexagonal-shaped maneuver.

5.2 Analysis of Current Vectors

Speed over water, as measured by a device located on the belly of the float body of the Wave Glider, is the velocity of the Wave Glider relative to the water it is traveling in. Since the vehicle travels in a medium that can be moving at the same time, any changes to vehicle speed must be looked at with reference to this fact. For example, if the vehicle is moving West with a water speed of 2 knots in a current moving with a speed of 1 knot in the same direction, then the vehicle is actually making 3 knots of speed over ground. Conversely, if the current is opposing the vehicle's direction of movement, the speed over ground will be only one knot. These examples are described in Figure 5.4 using vector arithmetic.

Since the ocean current is not directly measured and would be useful for analysis of vehicle performance, it can be estimated using speed over water, speed over ground, and heading data. While the calculation of the magnitude of the current velocity is a relatively basic exercise and can provide some insights, the current direction is a more useful parameter for further analysis, and can provide the most value in determining why the vehicle water speed changed so abruptly

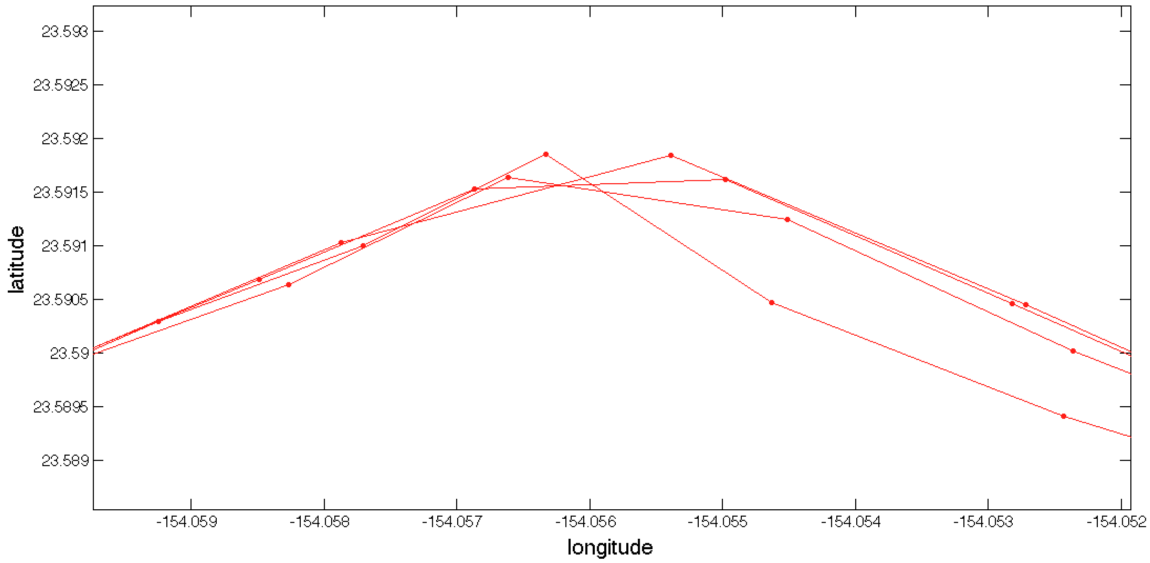

Figure 5.2: Wave Glider *Benjamin* zoomed look at one leg of NOAA NDBC Station 51000 circumnavigation showing minimal cross track error over several legs. Note: 0.001 degrees of latitude is approximately 100 meters

after the course change.

Based on speed over water plotted against time in Figure 5.5, there is no resulting reduction in speed over water or subsequent increase due to a course change until the final course is achieved. Since the speed over water magnitude stays constant over the maneuver, there appears to be no indication of a current affecting the propulsion system as shown in Figure 5.7. Looking at a plot of wind speed, wave height and period, and speed over water normalized over the same time frame shown in Figure 5.6, no significant changes in any of the relevant parameters explain the water-speed change either. It appears that the water-speed sensor is not providing accurate data in this instance. The cause is undertermined based on the data available.

5.3 14 February 2012 Course Anomaly

On 14 February 2012, *Benjamin* appears to have veered off the prescribed track and even moved backwards for a period of time before zig-zagging its way back on course, seen in Figure 5.8. Since there are no other instances of this type of behavior, an inspection of the cause is imperative.

There are a few hypotheses for this type of behavior. First, the vehicle could have been pushed

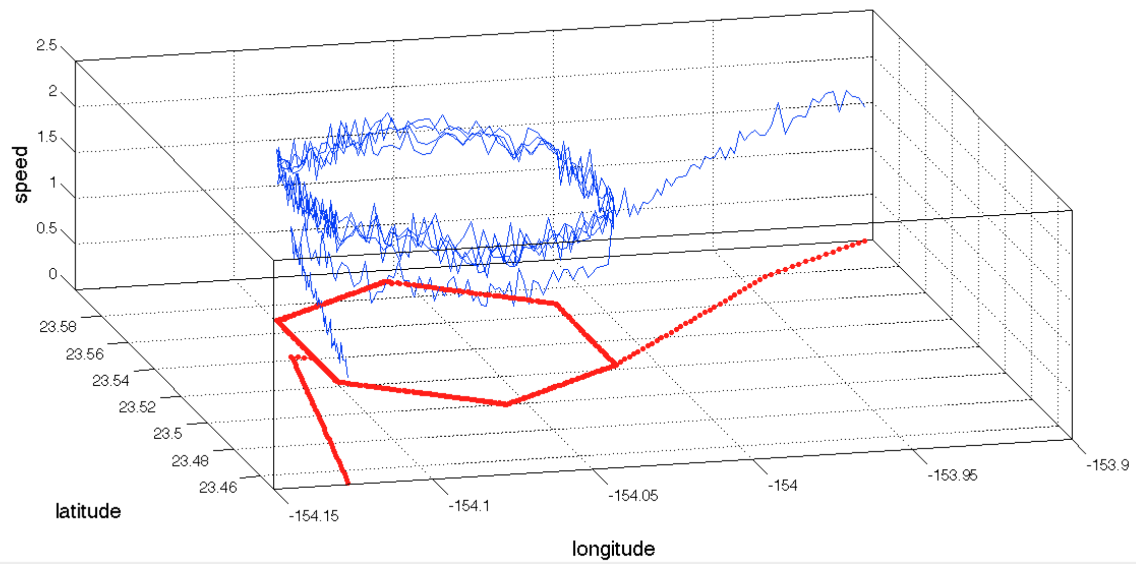

Figure 5.3: Wave Glider *Benjamin* transit around NDBC Station 51000

off track by environmental factors. Significant wave heights or swirling seas have the potential to overpower the propulsion system and force the vehicle off track. Also, a strong current could have prevented the vehicle from maintaining track as well, but it is unlikely that a current strong enough to affect the Wave Glider would be that short lived or that localized.

Looking at the speed over water data from the time period, there is no noticeable change in the magnitude. This is cause for concern. Just by examining the plotted positions taken at five-minute intervals, it is clear that the vehicle changed speed significantly during this event based on spacing between plotted positions.

Wind speeds recorded onboard *Benjamin* and NOAA weather service reports from 14 February to 18 February indicate a storm passing through the area. The average wind speeds recorded peaked at near 50 knots and were above 20 knots for much of the rest of the event. This is further evidenced by lower pressure recorded on *Benjamin's* barometer in the weather station. Wave height and wave period did not change significantly during the anomaly, with heights between two and four meters throughout, which is inconsistent with the presence of a major storm. The only evidence that a storm affected *Benjamin* is course deviation and it is not reflected in the speed over water. These results are shown in Figures 5.9 and 5.8.

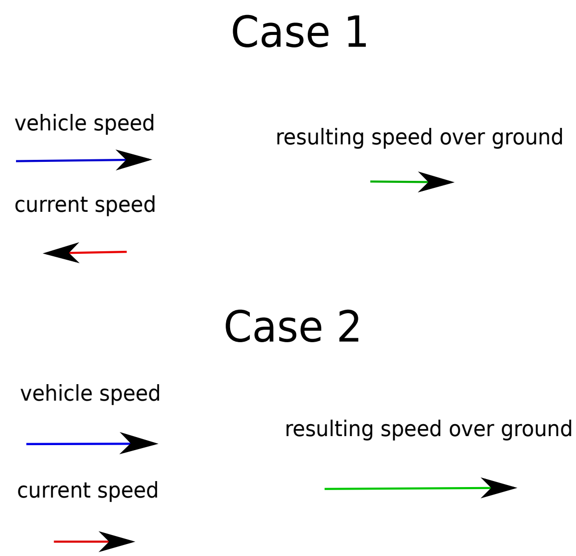

Figure 5.4: Physical description of current vector forces on a moving body

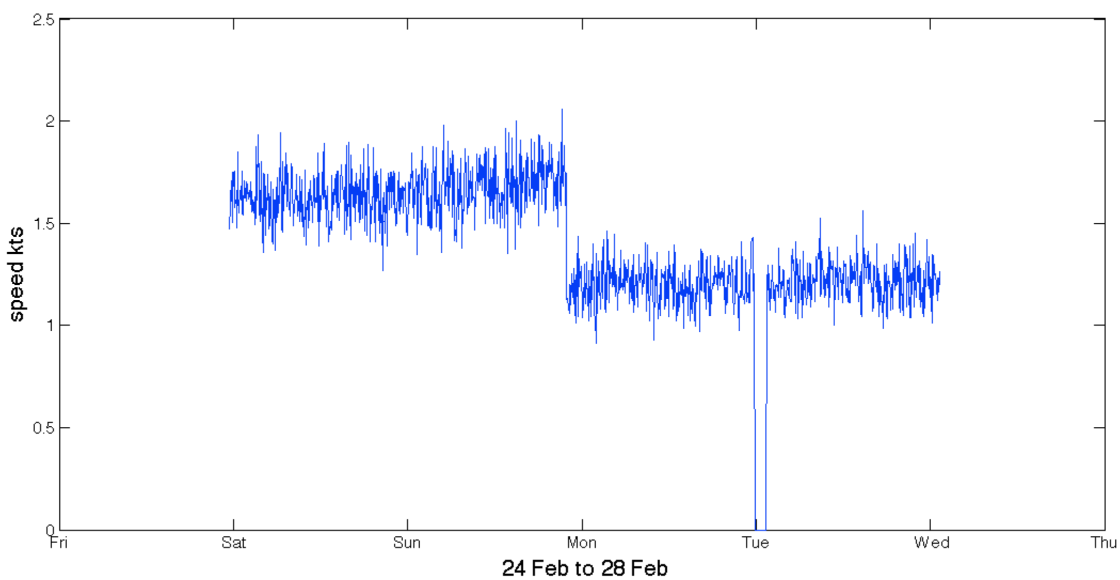

Figure 5.5: Water speed during Station 51000 circumnavigation

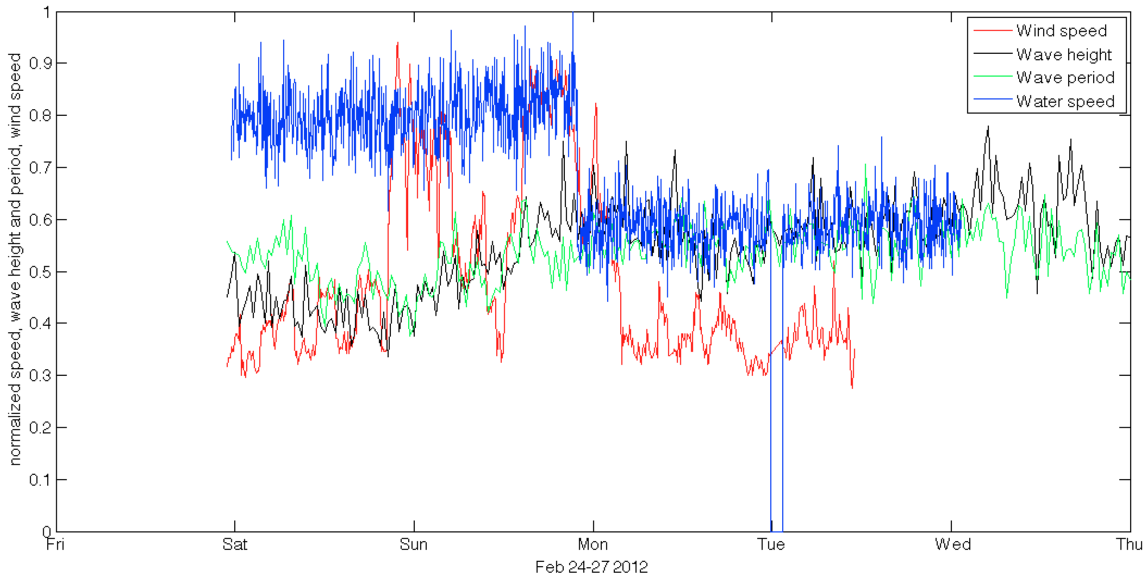

Figure 5.6: Water speed, wave height, wind speed and wave period during Station 51000 circumnavigation normalized and plotted on the same axis for trend analysis

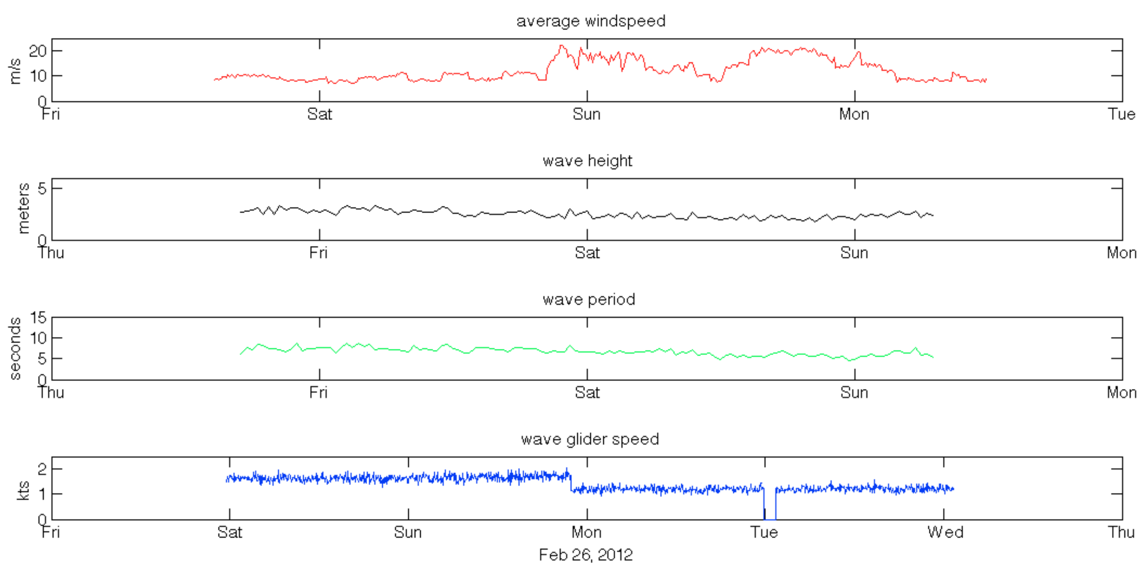

Figure 5.7: Water speed, wave height, wind speed and wave period during Station 51000 circumnavigation plotted on separate axes

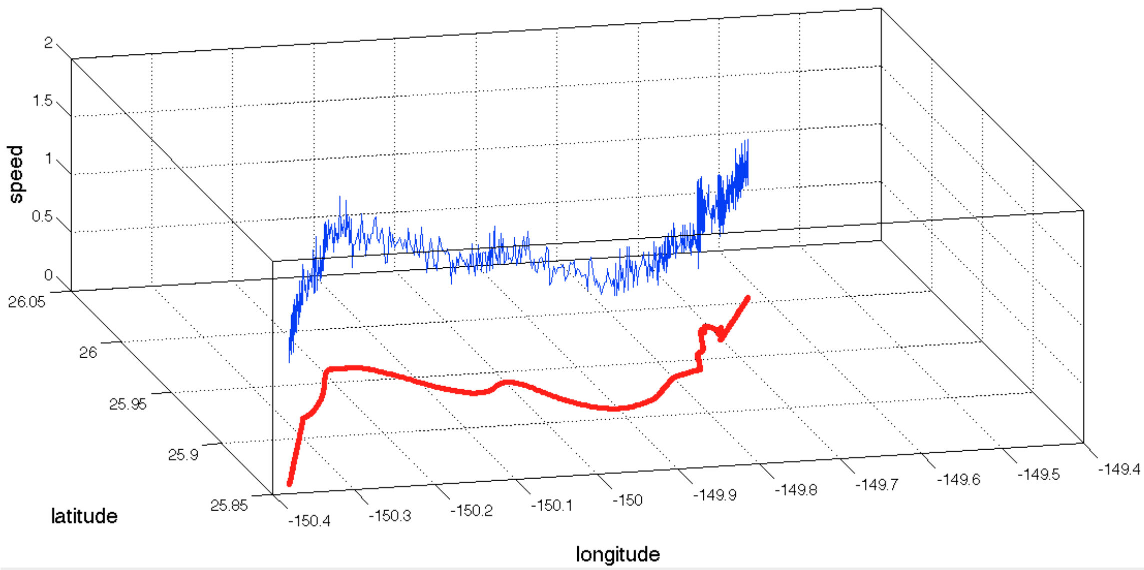

Figure 5.8: February 14-18 2012 *Benjamin* track and speed during storm conditions

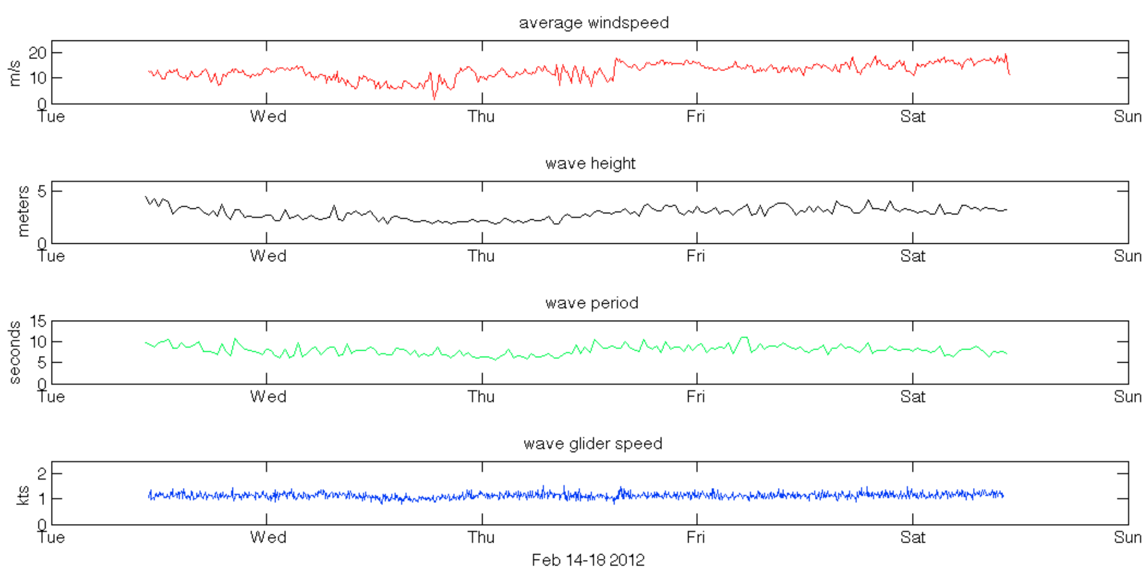

Figure 5.9: February 14-18 2012 *Benjamin* wind speed, wave height and period, and water speed during storm conditions

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CHAPTER 6:
Proposed Wave Glider Experiment

The PAC X experiment was designed as an oceanographic experiment and as a showcase for the LRI Wave Glider technology. As such, there are limited data available for investigating the propulsion system of the vehicles involved. Also, when a need arose to conserve power, the first instrument to be cycled off was the speed over water sensor. While some data are available to analyze the propulsion-system performance, a Wave Glider deployment specifically designed for a gateway-node mission would be useful in future analysis.

The Naval Postgraduate School has recently acquired two Wave Gliders for research in UDN systems. These vehicles can be outfitted with specific instruments needed to analyze a potential gateway-node deployment. Based on the knowledge gaps that need to be filled prior to reaching a definitive assessment of the Wave Glider, this thesis proposes a new experiment designed to test the Wave Glider for use in a gatekeeper application.

Based on previous analysis of available data sets, elements of a future experiment designed to prove the usefulness of the Wave Glider as a gatekeeper node must include three major considerations discussed in the following sections.

6.1 Power Consumption

To determine if the power production of the solar panels and energy storage of the batteries are sufficient, an acoustic modem needs to be integrated into the vehicle [13]. Experimentation with a modem-equipped Wave Glider will test the design of a modified USV and determine what, if any, effects there are on propulsion performance by adding more drag to the system. The acoustic modem that most resembles what will be deployed in Deep Seaweb is the Teledyne Benthos ATM-900 series. These modems use an average input power of 12-36 Volts DC and transmit at between 2 and 20 Watts depending on power setting and range desired. The acoustic modem weighs approximately 20 lbs [25].

During PAC X, the power was cycled to instruments regularly conserve energy for more critical loads as prioritized by the LRI operators. A Navy-led experiment focused on gatekeeper operations will have different priorities, and must ensure that the instruments needed for the effective operation of the underwater network remain the highest priority in the hotel power budget. This

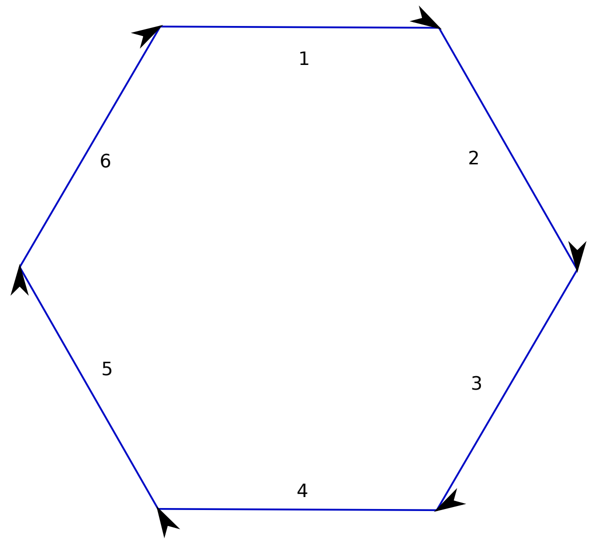

Figure 6.1: Proposed course design for ocean current analysis on the Wave Glider

operationally guided assessment would allow for proper diagnosis of the power requirements and associated supply from the Wave Glider.

6.2 Currents and Water Speed

Currents are an integral factor in the analysis of Wave Glider performance in a given environment. In the PAC X experiment, there was no ability to directly monitor the in situ current profile with available onboard sensors. This shortcoming can be corrected by adding an acoustic doppler current profiler (ADCP) to the float portion of the vehicle.

An ADCP will allow for current measurements at various depths with respect to the vehicle's float and glider portion. This would provide for a robust study of currents and the interaction between the float and glider.

Using the currents measured by the onboard ADCP and accurate heading data from the glider body of the vehicle, a more accurate analysis of the speed of the vehicle can be calculated. Using a six leg hexagonal course similar to the course used to circumnavigate NOAA NBDC station 51000 (see Section 5.1), one can mathematically represent the actual speed of the Wave Glider. Illustrated in Figure 6.1, with the legs numbered one through six, with one and four parallel opposites, two and five, and three and six similarly paired, the equations describing the velocity vectors are

$$\vec{V}_{actual} = \vec{V}_{WGi} + \vec{V}_{current} \quad i = 1,...,6 \tag{6.1}$$

where $\vec{V}_{actual}$ is the actual velocity of the Wave Glider (speed over ground) and $\vec{V}_{WGi}$ is the Wave Glider sensed velocity (speed over water) on a given leg i and $\vec{V}_{current}$ is measured current velocity.

$$|v_{actuali}| = |v_{WGi}| + |v_{current}|\cos(\theta_{WGi} - \theta_{current}) \tag{6.2}$$

where $|v_{actuali}|$ is magnitude of the actual velocity of the Wave Glider (speed over ground), $|v_{WGi}|$ is the magnitude of the Wave Glider sensed velocity(speed over water) on a given leg i, θ_{WGi} is the heading of the glider body on leg i, and $\theta_{current}$ is the current velocity vector angle.

$$|v_{act2}| - |v_{act5}| = |v_{WG2}| - |v_{WG5}| + |v_{current}|(\cos(\theta_2 - \theta_{current}) - \cos(\theta_5 - \theta_{current})) \tag{6.3}$$

As shown in equation 6.3, speed over water of the Wave Glider can be estimated using current velocity, vehicle heading and speed over ground.

This system of equations allows for solving of the Wave Glider speed over water, the water current, or the speed over ground depending on what known data are available. As it is difficult to measure speed over water so close to the surface of the ocean due to surface action in the form of ripples and wave chop, this method allows for a more robust water-speed calculation using current and speed over ground derived from GPS track data.

6.3 Mission Log

Perhaps the most important factor in creating a better experiment is the use of a mission log. LRI did not provide a mission log along with the data provided. This omission is perhaps the most significant drawback to the PAC X experiment for a propulsion system analysis. When anomalies in the data occur, or a direction is changed, or an uncharacteristic maneuver occurs, there is no way to determine the cause other than through inference based on the instruments onboard.

A proper mission should include at a minimum items such as any operator-inputted course changes deviating from the original track plan, date and time of key waypoints, interations with other ocean-going vessels inside sensor detection ranges, changes to weather patterns or sea states, and battery power level at regualr intervals. This is not an all-inclusive list, but identifies the types of items that require logging to ensure available explanation when conducting analysis. A Navy-led experiment focused on the gatekeeper application should ensure that it does not omit these experimental controls. A robust mission log that keeps a record of all system changes and observations throughout the experiment is essential for post-mission analysis of performance. Just as Naval ships keep deck logs to track the operations of the ship, a successful experiment utilizing sea-going vessels must maintain a running history of all occurences during the experiment. The Navy's Operational Test and Evaluation Force (OPTEVFOR) outlines specific items to be included in a mission log for test and evaluation, defined as an Operational Test Director Journal [26].

CHAPTER 7:
Conclusions

7.1 Wave Glider Impressions

The Wave Glider USV is a persistent, energy-harvesting, open-ocean platform that has many desirable characteristics for use in numerous applications. As a demonstration of capability, four Wave Gliders are performing a transit of the Pacific Ocean, in an event called PAC X. Using the PAC X experiment as a case study in the operation of the Wave Glider, some substantive conclusions can be made.

The vehicle has shown the capability to deploy for several months continuously in open-ocean conditions. The SATCOM connectivity of the platform was not an issue on three of the four vehicles deployed. The fourth vehicle, *Papa Mau*, had a software issue that led to loss of command and control to the vehicle. Numerous times during the voyage to Hawaii, data were unavailable for analysis due to outages.

There were some significant issues that presented themselves along the first leg of the journey. Wave Glider *Benjamin* was blown off course due to high wind and sea state during a four-day period in February, whose state was undiagnosable from onboard instruments other than GPS position. Again, a few weeks later, *Benjamin* circled a buoy for sensor calibration and a significant speed over water reduction occurred that is inexplicable using data from onboard instruments or other sources.

A shark attack left the *Piccard Maru* with a broken rudder approximately 200 miles from Hawaii. This was not the first time that a Wave Glider has been attacked by marine life [23]. The shark most likely was attracted to fish that tend to congregate around the shade produced from the float body of the vehicle.

In short, the Wave Glider is a well-performing USV that requires little command and control from shore to operate. It is not a 24-hours-a-day, 7-day-a-week platform for persistent communications or data collection. The Wave Glider did not demonstrat the ability to maintain constant coverage during the PAC X experiment. It has demonstrated the ability to maintan coverage a majority of the time. In systems that require constant coverage, the Wave Glider may not be suitable.

7.2 Potential Use as a Gateway Node

Future UDN systems must maintain continuous connectivity to shore because an event worth reporting can occur at any moment. The acoustic modem to be integrated into the Wave Glider will require hotel power that is different than the instruments deployed during the PAC X experiment.

Based on the results of the PAC X experiment, there is insufficient evidence to make a decision on the use of a Wave Glider as a replacement for the moored gateway buoy. Some lingering questions remain. More analysis into the exact power-consumption requirements of the acoustic modem and how that compares with what power is available on the Wave Glider is one area in need of further focus. Future UDN systems will require continuous coverage of the network by the gateway node and the results of this analysis are not conclusive as to whether the Wave Glider can perform this task.

The Wave Glider is a significant step toward providing an alternative to the existing moored gateway node. There are upsides to the Wave Glider platform that may outweigh its limitations. The extended range, tighter watch circle, and capacity to reposition itself autonomously are advantages that the Wave Glider provides over a moored system. More analysis must be conducted to determine the suitability of the Wave Glider for UDN systems and a way forward is to conduct an experiment designed to specifically examine the questions raised in this research.

Because of the surface/subsurface interface design that the Wave Glider embodies, it provides a platform that would be useful for communication with UUVs deployed in nearby areas. One difficulty in UUV operation is the ability to operate at or near the surface. The Wave Glider could provide a useful link in communication with UUVs via an acoustic path, allowing the UUV to stay submerged completely while communicating. This would eliminate the need for the UUV to surface or extend a mast above the water line to transmit comms to decision makers.

7.3 Other Potential DOD Applications

The Department of Defense is already using the Wave Glider experimentally. For example, SPAWAR Systems Center Pacific is conducting research on a passive acoustic towed array that can be deployed on the Wave Glider.

Perhaps the most important application to the Navy and Department of Defense is the Wave Glider's potential use in oceanographic observation. The Naval Oceanographic Office recently deployed two Wave Gliders to the Pacific and used them as METOC-gathering platform for the RIMPAC fleet exercise near Hawaii.

Another application for such ocean-going platforms is environmental sensing or pollution monitoring, such as oil spill detection and other hazardous materials. For example, the commercial oil and gas industry has effectively used the Wave Glider platform in the Gulf of Mexico as a sensor for detecting floating oil pockets after the Deepwater Horizon disaster in 2010 [8].

7.4 Operational Viability

The Wave Glider is a persistent maritime asset that requires no fuel to operate. Such energy-harvesting platforms are becoming more and more relevant as fossil fuels become more expensive. It's propulsion system provides for significant cost reduction and on-station time that far exceeds traditional surface platforms.

These benefits are not without some drawbacks, however. First, due to the nature of a wave-powered propulsion system, the vehicle is slow. Assets must be deployed weeks or months in advance, depending on the distance required to be traveled and the accessibility of the area to manned platforms that can launch the Wave Glider. The slow operation of the vehicle also prevents use in high-traffic areas as it cannot maneuver sufficiently to avoid collision or entanglement with fishing nets. Second, because of the limitations on current size and payload, only relatively small sensors can be hosted on the Wave Glider, making them somewhat limited in use. Lastly, because of the limited power-generation capabilities (from solar) and payload power requirements, the Wave Glider will likely be unable to provide 100 percent coverage or connectivity. Storms, long periods of overcast skies, and high currents will limit the effectiveness of the Wave Glider in some situations.

The Wave Glider can be a useful tool in the arsenal of unmanned systems that the Department of Defense is using. It is not the answer to every problem out there, but for some applications it has great potential.

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Appendix: PAC X Data Analysis Matlab Code

All source code developed and used for this thesis can be found online at `https://faculty.nps.edu/thchung` under the *Software* section.

The following Matlab code was used to develop the variables of interest for all of the plots shown in this thesis. The data was uploaded to Matlab from the PAC X website in CSV format and manipulated via this code. All times in the data files were converted from UTC times to a vector date format for ease of display and understanding while plotting.

```
%01 March 2012_Tim Rochholz_Naval Postgraduate School   Code for PAC X
%propulsion system performance analysis.  Data sets below available at
%pacxdata.liquidr.com

clear
clc

% Load the saved data file
load('winddata.mat')
load('wavedata.mat')
load('speeddata.mat')


%the data starts on 13 Nov 2011 00:01:05 and ends on 20 Apr 2012 18:32:20
%GMT.  The partal data set used for a smaller cross section of data starts
%on 21 Feb 2012 18:11:42 and ends on 06 Mar 2012 06:44:13 GMT.  These times
%are taken from the speed data set known as 'speeddata' since there is
%minor differences between the three data sets, I used this set as the
%standard.

%this is the initial program to determine maxes and mins and set up all the
%variables for creating plots for speed, wind speed, and wave data.
%wind data is under the name weatherBenjamin, speed data is under
%basicBenjamin, and wave data is under DatawellMOSEBenjamin. Each different
%data set has associated times and lat/long data associated with their time
%series data

%the units for each of the data sets are as follows:  waterspeed in kts,
%wave period in seconds, wave height in meters, longitude and latitude in
%degrees E and N respectively, wind speed in m/s

%parameter values not normalized for use in subplots, etc

speed=basicBenjamin.waterSpeed;

wind=weatherBenjamin.avgWindSpeed;
```

```
wave=DatawellMOSEBenjamin.Hs;

period=DatawellMOSEBenjamin.Tav;

lat=basicBenjamin.latitude;

long=basicBenjamin.longitude;

%max values for use in normalized graphing functions and other applications
%from the entire data set

maxspeed = max (speed);

maxwind = max (wind);

maxwave = max (wave);

maxperiod = max (period);

%max values for use in normalized grapthing functions using the defined
%data boundaries

maxspeed1= max (speed(22803:26905));

maxwind1 = max (wind(8948:10920));

maxwave1 = max (wave(2641:3212));

maxperiod1 = max (period(2641:3212));



% wind data is every 10 min, wave data every 30 min and speed/position data
% every 5 min

speedinterval=basicBenjamin.time;

windinterval=weatherBenjamin.time;

waveinterval=DatawellMOSEBenjamin.time;

%wind, wave and speed time data converted from UTC to an actual date


speeddate=datevec(datenum(1970,1,1)+basicBenjamin.time/86400);

winddate=datevec(datenum(1970,1,1)+weatherBenjamin.time/86400);

wavedate=datevec(datenum(1970,1,1)+DatawellMOSEBenjamin.time/86400);
```

```
%normalized values for the parameters over the entire data set

normspeed=speed/maxspeed;

normwind=wind/maxwind;

normwave=wave/maxwave;

normperiod=period/maxperiod;

%normalized values for the parameters over the defined data boundaries


normspeed1=speed/maxspeed1;

normwind1=wind/maxwind1;

normwave1=wave/maxwave1;

normperiod1=period/maxperiod1;

%average values of wave height, wind speed, wave period and speed over the
%given range

meanspeed1= mean (speed(22803:26905));

meanwind1 = mean (wind(8948:10920));

meanwave1 = mean (wave(2641:3212));

meanperiod1 = mean (period(2641:3212));



%distance travelled during the given range using lat and long from speed
%data in KM

dist=pos2dist(37.4109,122.0047,20.0380,155.8306,1);



%speed of the vehicle averaged over the straight line distance in nm/hr.
%.539956 is the conversion from kilometers to nm.  324.54 is the number of
%hours of the whole trip

spdavg=dist*(.539956)/2256;
```

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REFERENCES

[1] R. Hine, “PAC X Experiment Wave Glider Launch,” San Francisco, Ca, 2011.

[2] J. A. Rice, “Seaweb Acoustic Communication and navigation efforts,” in *Proceedings of the International Conference Underwater Acoustic Measurements: Technologies & Results*, Heraklion, Greece, 2005.

[3] ——, “Gatekeeper Station-Keeping Gateway Buoy,” Office of Naval Research, San Diego, CA, Tech. Rep., 2005.

[4] R. Smith and J. Das, “Predicting wave glider speed from environmental measurements,” *Proceeding fo MTS/IEEE Oceans 2011*, 2011.

[5] DOD, “SBIR Topic N05-077 “Gatekeeper Station-Keeping Gateway Buoy”,” Washington, DC, 2004.

[6] R. Hine, S. Willcox, G. Hine, and T. Richardson, “The Wave Glider: A wave-powered autonomous marine vehicle,” in *Proceedings of OCEANS 2009, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges*. IEEE, 2009, pp. 1–6.

[7] J. Manley and S. Willcox, “The Wave Glider: A persistent platform for ocean science,” in *Proceedings of OCEANS 2010 IEEE-Sydney*. IEEE, 2010, pp. 1–5.

[8] T. Daniel, J. Manley, and N. Trenaman, “The Wave Glider: enabling a new approach to persistent ocean observation and research,” *Ocean Dynamics*, pp. 1–12, 2011.

[9] S. Wiggins, J. Manley, E. Brager, and B. Woolhiser, “Monitoring marine mammal acoustics using Wave Glider,” in *Proceedings of OCEANS 2010*. IEEE, 2010, pp. 1–4.

[10] LRI, “Liquid Robotics Pacific Crossing Data,” 2012. [Online]. Available: http://pacxdata.liquidr.com

[11] S. Thompson, “Displacement of Tethered Hydro-Acoustic Modems by Uniform Horizontal Currents,” Masters Thesis, Naval Postgraduate School, 2009.

[12] ——, “Sound Propagation Considerations For a Deep Ocean Acoustic Network,” Masters Thesis, Naval Postgraduate School, 2009.

[13] J. Beach, "Integration of an Acoustic Modem onto A Wave Glider Unmanned Surface Vehicle," Masters Thesis, Naval Postgraduate School, 2012.

[14] H. Luan, O. C. Onar, and A. Khaligh, "Dynamic Modeling and Optimum Load Control of a PM Linear Generator for Ocean Wave Energy Harvesting Application," in *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*. IEEE, Feb. 2009, pp. 739–743.

[15] S. Bastien, R. Sepe, A. Grilli, S. Grilli, and M. Spaulding, "Ocean wave energy harvesting buoy for sensors," in *2009 IEEE Energy Conversion Congress and Exposition*. IEEE, Sep. 2009, pp. 3718–3725.

[16] J. Falnes and J. r. Lø vseth, "Ocean wave energy," *Energy Policy*, vol. 19, no. 8, pp. 768–775, Oct. 1991.

[17] J. Rice, "Report on Preliminary WAHAS Tests," Naval Ocean Systems Center, San Diego, CA, Tech. Rep., 1982.

[18] G. O. Pickens, "Wave-Actuated Horizontal Array Stretcher Patent No. 3,872,819," 1976.

[19] D. A. Read, F. S. Hover and M. S. Triantafyllou, "Forces on oscillating foils for propulsion and maneuvering," *Journal of Fluids and Structures*, vol. 17, pp. 163–183, 2002.

[20] G. L. Pickard and W. J. Emery, *Descriptive Physical Oceanography*, 5th ed. Oxford: Elsevier, 1990, vol. 7.

[21] MATLAB, *version 7.14.0 (R2012a)*. Natick, Massachusetts: The MathWorks Inc., 2012.

[22] N. Bowditch, *The American Practical Navigator, 1995 edition*. Bethesda: Defense Mapping Agency, 1995.

[23] S. Willcox, J. Manley, and S. Wiggins, "The Wave Glider, an Energy Harvesting Autonomous Surface Vessel: Persistent presence enables acoustic operations as a virtual buoy or mobile platform," *Sea Technology*, 2009.

[24] N. O. US Department of Commerce and A. Administration, "National Data Buoy Center," 2012. [Online]. Available: http://www.ndbc.noaa.gov/

[25] TeledyneBenthos, "ATM-900 Series Acoustic Modems," North Falmouth, MA, 2011.

[26] COMOPTEVFOR, "Operational Test Director's Manual," Norfolk, VA, 2012.

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